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Artificial Intelligence Surgery

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Artificial intelligence in precise surgical planning for adolescent idiopathic scoliosis: applications and challenges

Yawei Zhang[1,#], Jingyu Liu[1,#], Zijie An[1], Qiaoyu Zhang[1], Yue Mao[2], Jia Zhu[2], Lianzong Hang[1], Rui Zhao[3], Kun Zhu[1,4]

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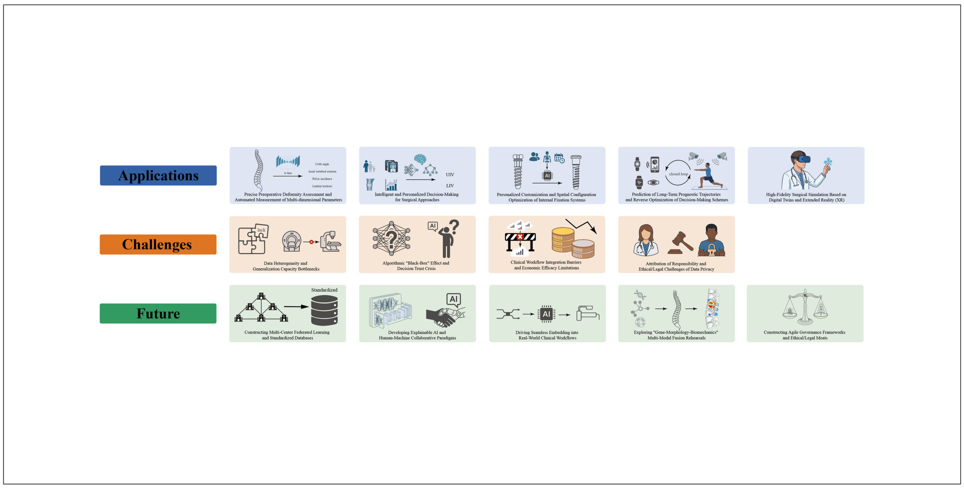

Abstract

Adolescent idiopathic scoliosis (AIS) is the most common three-dimensional spinal deformity among adolescents, characterized by a coronal curvature of > 10°, often accompanied by vertebral rotation and abnormal sagittal alignment, which can lead to severe cardiopulmonary and neurological dysfunction. For moderate-to-severe or progressive AIS (e.g., Cobb angle ≥ 45°), surgical intervention is the primary treatment modality. However, traditional surgical planning relies heavily on surgeons' clinical experience and is subject to substantial interobserver variability, making it difficult to fully meet the needs of personalized precision medicine. In recent years, advances in artificial intelligence (AI), particularly in machine learning and deep learning, have provided new methodological tools for precise surgical planning in AIS. This article reviews the main applications of AI in AIS surgical planning, including AI-assisted assessment and

[1]Department of Orthopedics, The First Affiliated Hospital of Bengbu Medical University, Bengbu 233000, Anhui, China.
[2]Department of Geriatric Medicine, The First Affiliated Hospital of Bengbu Medical University, Bengbu 233000, Anhui, China.
[3]Department of Basic Teaching of General Practice, The Second Affiliated Hospital of Bengbu Medical University (The Second Clinical College of Bengbu Medical University), Bengbu 233000, Anhui, China.
[4]Institute of Digital and Intelligent Healthcare, Bengbu Medical University, Bengbu 233000, Anhui, China.
[#]These authors contributed equally to this work.

Correspondence to: Dr. Kun Zhu, Department of Orthopedics, The First Affiliated Hospital of Bengbu Medical University, Bengbu 233000, Anhui, China. E-mail: drkunzhu@bbmu.edu.cn; Prof. Rui Zhao, Department of Basic Teaching of General Practice, The Second Affiliated Hospital of Bengbu Medical University (The Second Clinical College of Bengbu Medical University), Bengbu 233000, Anhui, China. E-mail: 2014035@bbmu.edu.cn

automated measurement of preoperative spinal deformities; personalized decision-making for surgical approaches and fusion levels; personalized biomechanical and finite element analysis (FEA)-based optimization of internal fixation devices; prediction of postoperative outcomes; and recent advances in 3D surgical simulation and navigation. Furthermore, this review examines the current limitations of translating AI models into clinical practice, such as data heterogeneity, the "black-box" nature of algorithms, and ethical and regulatory issues. It also discusses future directions, including multicenter federated learning and human-in-the-loop collaborative decision-making, and aims to provide a systematic overview to support intelligent and precise surgical treatment of AIS.

INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional spinal deformity of incompletely understood etiology that predominantly develops during puberty (10-18 years of age), accounting for 75% to 85% of all scoliosis cases[1]. The objectives of clinical intervention are to maximize deformity correction in three-dimensional space, halt curve progression, preserve cardiopulmonary and neurological function and maintain the physiological segmental mobility of the spine to the greatest extent possible. For patients with moderate-to-severe or rapidly progressive AIS (e.g., Cobb angle ≥ 45°), surgical intervention is the preferred and often necessary treatment modality[2]. The quality and precision of surgical planning directly influence the short-term efficacy of deformity correction and patients' long-term health-related quality of life (HRQOL).

Traditional AIS surgical planning relies heavily on surgeons' empirical interpretation of two-dimensional static imaging data, such as X-rays, computed tomography (CT), and magnetic resonance imaging (MRI), combined with subjective assessments of the patient's bone age and deformity classification. However, AIS exhibits marked anatomical heterogeneity, with substantial interpatient variation in the degree of coronal scoliosis, axial vertebral rotation, and sagittal imbalance[3]. Conventional manual parameter measurements (e.g., Cobb angle and degree of vertebral rotation) are time-consuming and subject to substantial interobserver variability and limited reproducibility[4]. More importantly, traditional static morphology-based evaluations cannot fully characterize changes in biomechanical properties during deformity correction or adequately evaluate local spinal stress distributions under complex physiological loads using finite element analysis[5]. This experience-based decision-making approach may lead to suboptimal selection of fusion levels and mismatched internal fixation devices, and may subsequently result in postoperative complications such as deformity recurrence, implant failure (e.g., rod breakage or screw pull-out), and adjacent segment disease (ASD)[6].

Artificial intelligence (AI) offers a potential means of addressing these clinical limitations. By integrating computer science, statistics, and modern medicine, AI can perform feature extraction and automated analysis of large, high-dimensional multimodal datasets (including clinical characteristics, multidimensional imaging, and biomechanical parameters)[7]. In recent years, AI applications in orthopedics have progressed from technical validation toward clinical decision support. Particularly in the precise quantitative assessment of preoperative deformities, 3D surgical trajectory planning, and prognostic risk stratification for AIS, AI has shown potential clinical value[8]. Accordingly, this narrative review summarizes recent evidence and provides an overview of the main applications of AI in precise AIS surgical planning [Figure 1], thereby supporting the transition of spine surgery toward data-driven, intelligent, and precise decision-making[9].

LITERATURE SEARCH STRATEGY

To conduct this narrative review, a literature search was performed using the PubMed, Web of Science, and Embase databases. The search covered the period from January 2020 to May 2026, using keywords including "adolescent idiopathic scoliosis", "artificial intelligence", "machine learning", "deep learning", and "surgical planning". Priority was given to studies addressing clinical translation, surgical simulation, and biomechanical optimization.

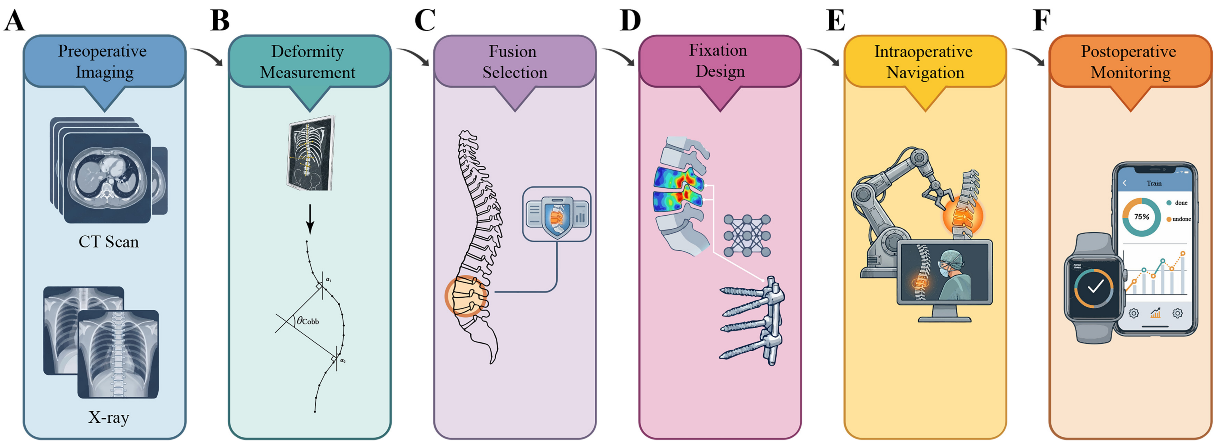

Figure 1. Clinical workflow pipeline. A horizontal flowchart tracing the patient journey. (A) Preoperative Imaging, utilizing CNNs for image processing; (B) Deformity Measurement, applying GCN/U-Net for parameter extraction; (C) Fusion Selection, employing random forest for decision support; (D) Fixation Design, integrating AI and FEA for personalized implant optimization; (E) Intraoperative Navigation, leveraging AR and computer vision for robotic execution; and (F) Postoperative Monitoring, utilizing wearables and deep learning for long-term surveillance. (Created with Adobe Illustrator by the authors.) CNNs: Convolutional neural networks; GCN: graph convolutional network; AI: artificial intelligence; FEA: finite element analysis; AR: augmented reality.

CORE APPLICATIONS OF AI IN SURGICAL PLANNING FOR AIS

Precise preoperative deformity assessment and automated measurement of multidimensional parameters

Precise quantitative characterization of spinal deformity before surgery is fundamental to AIS surgical planning. Relevant parameters include the coronal Cobb angle and axial vertebral rotation (e.g., Nash-Moe grade), as well as complex sagittal balance parameters (e.g., pelvic incidence and lumbar lordosis) and overall spinal flexibility[10]. These multidimensional data inform assignment of the Lenke classification, the setting of surgical correction targets, and the selection of fusion levels. Traditional manual measurement of parameters on two-dimensional static images is time-consuming and cognitively demanding and is strongly influenced by observer experience, resulting in poor measurement reproducibility and consistency. In contrast, AI technologies are improving the precision and efficiency of parameter assessment through deep feature extraction and automated analysis.

Currently, deep learning algorithms, particularly convolutional neural networks (CNNs) and their variants (e.g., U-Net), have enabled advances in the automated segmentation and parameter measurement of spinal images. A scoping review by Goldman et al. reported that up to 62.5% of AI applications related to AIS focused on imaging analysis, with over half concentrated on the automated measurement of Cobb angles and degrees of vertebral rotation. The overall mean model accuracy across all included AIS AI applications was reported to be 85.4%[11]. Multiple studies have confirmed that CNN-based end-to-end assessment systems can achieve precise vertebral segmentation and efficient automated Cobb angle measurement on full-length radiographs, with an absolute measurement error of less than 3°[11]; their intraclass correlation coefficients (ICCs) are consistently above 0.8, indicating greater reproducibility than manual measurement. For instance, the U-Net-based automated assessment system developed by the team at Peking Union Medical College Hospital achieved a high level of agreement with experts (with a κ value up to 0.989) in complex Lenke classification tasks, providing an objective quantitative basis for preoperative decision-making[12].

AI is also extending preoperative assessment from a single focus on "two-dimensional morphology" to three-dimensional multimodal and biomechanical assessment[11]. Using multimodal image fusion, AI models can align X-ray, CT, and MRI data to generate 3D spatial maps of osseous structures and soft-tissue characteristics[10]. Furthermore, for the dynamic assessment of spinal flexibility, AI can not only evaluate the range of motion by automatically tracking dynamic images (such as left- and right-bending or traction radiographs) but also automatically extract geometric contours and bone density distributions based on preoperative CT data, assisting in the rapid construction of high-fidelity personalized spinal finite element models (FEMs)[13]. This biomechanical approach may allow calculation of the 3D spatial stress distribution and correction potential of the spine preoperatively, thereby reducing errors in fusion-level selection caused by inadequate assessments of flexibility and stress.

Intelligent and personalized decision-making for surgical approaches

The precise definition of fusion levels and the selection of surgical approaches are central to the long-term efficacy of AIS surgery. The key clinical trade-off is how to achieve adequate three-dimensional correction while preserving the physiological motion segments of the spine (especially the lumbar spine) to avoid long-term postoperative complications[2,14]. Conventional decision-making based on surgeons' subjective experiences and standard guidelines (such as the Lenke criteria) often varies substantially among surgeons when dealing with complex, patient-specific deformity features and variable spinal flexibility[14]. Particularly in determining the upper instrumented vertebra (UIV) and the lowest instrumented vertebra (LIV), clinical experience alone may not reliably achieve the optimal balance between correction benefits and preservation of spinal motion: long-segment fusion can achieve adequate 3D correction but at the expense of spinal physiological mobility; conversely, if the fusion range is insufficient because of an effort to preserve motion segments, residual abnormal stress may contribute to postoperative deformity progression, distal adding-on, and ASD.

To address this trade-off, AI technologies have been developed to support personalized decisions by integrating multidimensional heterogeneous data (such as patient demographics, skeletal growth potential, multidimensional imaging parameters, and long-term follow-up outcomes). Decision support systems based on algorithms such as random forest, support vector machine (SVM), and deep neural networks can model the nonlinear relationships between individual features and optimal fusion ranges. For instance, machine learning algorithms have been utilized to construct predictive models for predicting rehabilitation outcomes in pediatric patients after spinal deformity surgery; notably, the random forest model demonstrated excellent predictive performance with an area under the receiver operating characteristic curve (AUROC) of 0.86 for short-term postoperative outcomes[15]. More recently, hybrid models that closely integrate AI algorithms with finite element analysis (FEA) can generate patient-specific spinal biomechanical models preoperatively. By simulating local stress conduction and load distribution under different LIV settings, the system may predict the risk of biomechanical overload in the lumbar spine and adjacent segments, thereby providing biomechanical evidence to help define optimal fusion boundaries[6].

In the optimization of surgical approaches and techniques, AI may also support decision-making[16]. When comparing surgical techniques such as posterior extensive fusion, anterior release and fusion, and minimally invasive deformity correction, AI models can comprehensively integrate anatomical parameters, sagittal compensatory pelvic tilt, and cardiopulmonary tolerance to perform multidimensional outcome simulations and surgical risk stratification[14]. By predicting sagittal spinopelvic compensatory mechanisms, these predictive models can assist surgeons in simulating and planning the optimal surgical strategy to support the intended deformity correction and maintain postoperative sagittal balance[17].

Personalized design and spatial optimization of internal fixation systems

The spatial layout and degree of biomechanical compatibility of internal fixation systems (e.g., pedicle screws and corrective rods) are important determinants of 3D correction efficacy in AIS and help prevent postoperative implant failure (e.g., screw loosening or rod breakage). In conventional surgery, standardized commercial internal fixation instruments may not fully accommodate the highly variable vertebral anatomy of AIS patients, particularly in the presence of severe rotation. Moreover, reliance on intraoperative freehand screw placement and empirical rod bending not only limits precision but also limits adaptation to complex local spinal stress distributions. In recent years, the deep integration of AI technologies with computer-aided design (CAD), 3D printing, and robot-assisted surgical navigation has created a potential closed-loop approach for the personalized optimization of internal fixation instruments.

On the one hand, regarding instrument customization and morphological matching, AI models can automate the extraction of 3D geometric features of target vertebrae (such as pedicle isthmus width, cortical bone thickness, and pedicle angle) based on high-precision thin-slice CT data. Based on these individualized parameters, AI can not only assist in designing patient-specific screws but also be integrated with FEA to simulate stress conduction and pull-out strength at the screw-bone interface under various physiological loads in a virtual environment, thereby using preoperative simulation to reduce the risk of biomechanical failure [Figure 2]. Advanced computational frameworks have demonstrated the feasibility of integrating AI with physics-based model simulations to optimize surgical planning. Such models can systematically evaluate and refine personalized instrumentation strategies - including the selection of optimal fusion levels, screw distribution, and rod design - prior to surgery, thereby adapting to complex spinal deformities and minimizing the risk of biomechanical failure[18].

On the other hand, for spatial planning and accurate implantation, AI combined with orthopedic surgical robots may improve procedural accuracy. Through the preoperative construction of digital twin models, AI algorithms can automatically plan the optimal screw implantation trajectory and depth, guiding the robotic arm to perform the planned procedure with submillimeter precision. Synthesized clinical evidence suggests that AI-enabled robot-assisted pedicle screw placement has a significantly higher success rate than conventional freehand techniques [equivalent odds ratio (eOR) = 2.74][19] [Table 1]. Furthermore, regarding the optimization of the spatial configuration of corrective internal fixation rods (such as titanium alloy or cobalt-chromium alloy), the design of implant rod curvature directly determines the reconstruction quality of sagittal balance. As confirmed by the classic biomechanical studies of Salmingo *et al.*, advanced computational analyses of *in vivo* rod deformation have clarified the biomechanical effects of pre-bending curvature on correction efficacy[20]. Building on this work, AI-assisted systems can predict and compensate for the "spring-back effect" based on the elastic modulus and deformation laws of different materials and calculate the optimal personalized pre-bending curvature[21]. This can provide a quantitative basis for achieving standardized, precise pre-bending using numerical control equipment before surgery, reduce metal fatigue and stress concentration caused by repeated manual intraoperative rod bending, and help restore the patient's ideal physiological sagittal curvature (e.g., lumbar lordosis), thereby improving the long-term maintenance of correction rates and surgical efficiency.

Prediction of long-term outcomes and optimization of surgical planning

The ultimate goal of surgical treatment for AIS extends beyond immediate three-dimensional deformity correction to the long-term maintenance of spinal function and the improvement of patients' HRQOL scores[22]. Therefore, it is important to incorporate long-term prognostic risks (such as deformity progression, implant failure, adjacent segment degeneration, and neurological dysfunction) into preoperative decision-making models. Traditional prognostic assessments rely heavily on surgeons' subjective clinical experience; complex, heterogeneous multidimensional baseline data may obscure clinically relevant risk factors. In

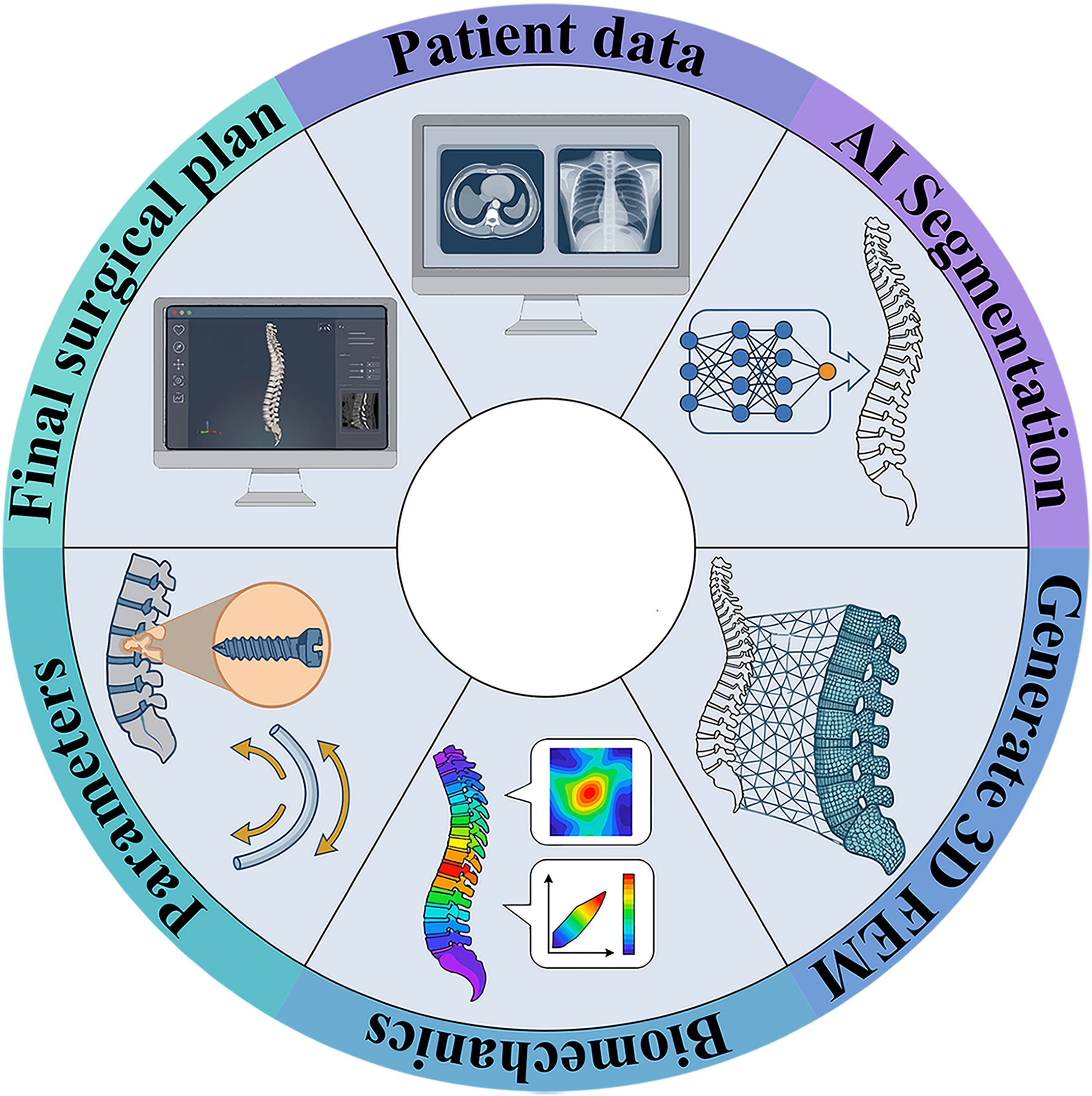

Figure 2. AI-FEA integration loop. A schematic showing the workflow of the closed-loop system: Patient CT and X-ray data undergo AI-based segmentation to generate a 3D FEM. This model feeds into biomechanical simulation to determine the optimal trajectory and personalized rod bending, ultimately informing the final surgical plan. (Created with Adobe Illustrator by the authors.) AI: Artificial intelligence; FEA: finite element analysis; CT: computed tomography; FEM: finite element model.

Table 1. Summary of representative AI applications and evidence in AIS surgical planning

Clinical task	AI technology	Evidence source	Key findings/Performance highlights
Cobb angle detection	CNN/U-Net	Scoping review[11]	Reported an overall mean model performance accuracy of 85.4% across all included AIS AI applications, rather than an angle-specific metric
Postoperative outcome/HRQOL prediction	Random Forest	Cohort study[15]	Demonstrated robust predictive ability with an AUROC of 0.86 for short-term postoperative outcomes (e.g., SRS-22R)
Pedicle screw placement	Robot/ AR Navigation	Meta-analysis[19]	Demonstrated a significantly higher success rate for acceptable pedicle screw placement than conventional freehand techniques (eOR = 2.74)

This table summarizes representative evidence for distinct AI applications. Findings are derived from different literature sources and clinical tasks; therefore, they are presented contextually and are not intended for cross-task comparison. Additionally, regarding pedicle screw placement[19], the synthesized success rate (eOR) represents clinically acceptable placement, typically defined as Gertzbein-Robbins grade A or B. AI: Artificial intelligence; AIS: adolescent idiopathic scoliosis; CNN: convolutional neural network; U-Net: U-shaped network; AR: augmented reality; AUROC: area under the receiver operating characteristic curve; HRQOL: health-related quality of life; SRS-22R: Scoliosis Research Society-22 Revised; eOR: equivalent odds ratio.

contrast, AI technologies can use high-dimensional clinical features to develop risk stratification and models for predicting prognostic trajectories, thereby providing information for the prospective optimization of surgical strategies.

Leveraging machine learning architectures, researchers can integrate features such as demographics, multidimensional imaging parameters, proposed fusion ranges, and expected blood loss to estimate individualized postoperative outcomes. For example, recent clinical cohort studies have trained machine learning models - such as random forests and neural networks - to predict short- and medium-term Scoliosis Research Society-22 Revised (SRS-22R) scores postoperatively using multidimensional baseline features. These predictive models have achieved AUROC values exceeding 0.80[15]. Of greater clinical relevance, explainability analyses within these systems have quantified the influence of sagittal balance parameters (e.g., lumbar lordosis angle, sagittal vertical axis) and patients' preoperative self-image on long-term quality of life. These findings may help refine sagittal remodeling targets during surgery and rehabilitation interventions after ambulation[23].

Furthermore, during long-term postoperative follow-up and rehabilitation, AI may also support automated monitoring. On the one hand, by deploying automated image analysis systems based on deep network architectures such as CNNs, clinicians can perform high-throughput comparisons of serial postoperative X-rays[11]. Specifically, deep learning models have achieved reliable automated classification of pediatric spinal radiographs, enabling the efficient establishment of large-scale, standardized longitudinal imaging registries. This high-throughput automated categorization provides a crucial data foundation for future intelligent surveillance systems to effectively track postoperative outcomes and device status[24]. On the other hand, combining wearable sensors and computer vision technologies, AI is also being applied to digital postoperative rehabilitation, supporting continuous monitoring of the recovery of spinal biomechanical balance in patients and the formulation of personalized exercise prescriptions[25].

High-fidelity surgical simulation based on digital twins and extended reality

AIS corrective surgery involves complex 3D spatial remodeling of anatomical structures and delicate procedures adjacent to critical neurovascular bundles, resulting in a steep technical learning curve and a risk of complications. Implementing high-fidelity digital twins and simulation rehearsals preoperatively may be clinically valuable for shortening the learning curve, optimizing surgical trajectories, and controlling intraoperative risks. In recent years, the deep integration of AI technologies with extended reality (XR), including virtual reality (VR) and augmented reality (AR) and 3D printing technologies has advanced AIS surgical simulation by enabling immersive interaction and biomechanical quantification.

For comprehensive preoperative simulation, AI algorithms can perform automated, high-precision segmentation of patients' multimodal images (CT, MRI) to generate high-resolution 3D models encompassing bones, the spinal cord, and nerve roots[11]. In an interactive VR environment, surgeons can view the anatomy from any angle and perform virtual osteotomy planning to accurately identify anatomical variations and surgical blind spots; when combined with AI-driven FEA, the system can dynamically simulate biomechanical responses and stress distributions during operations such as osteotomy correction and internal fixation device implantation. Such dynamic simulations based on biomechanical feedback may reduce the risks of cortical bone rupture or implant pull-out caused by over-correction[13]. Additionally, as shown in recent clinical applications[26], utilizing AI to precisely calculate deformity parameters and support the production of 1:1 physical anatomical models via 3D printing can provide realistic tactile feedback for preoperative in vitro rehearsals. This approach can achieve submillimeter procedural precision and may improve surgical safety and efficacy.

During intraoperative execution, AR technology enables the mapping of preoperative digital plans onto the surgical field through high-precision spatial registration. Using advanced multimodal spatial registration algorithms, AR technology can accurately superimpose the optimal screw trajectories and 3D virtual anatomical views planned preoperatively by AI onto the patient's open surgical field in the form of holographic images. This real-time, in situ integration of virtual plans with the surgical field effectively reduces the cognitive load on surgeons by minimizing the need to switch visual focus between the actual anatomy and external displays. It may enhance the surgical precision and efficiency of complex AIS deformity corrections and may also reduce surgical time and intraoperative radiation exposure.

CURRENT PROBLEMS AND CHALLENGES

Although AI has demonstrated considerable potential in the field of precise surgical planning for AIS, its transition from proof-of-concept to large-scale clinical application still faces several important barriers.

Data heterogeneity and generalizability bottlenecks

The construction of high-precision AI models relies heavily on large-scale, standardized, multimodal clinical cohort data with high-quality annotations. However, current datasets in the AIS field generally suffer from limited sample sizes, pronounced data silos across centers, and a lack of unified annotation paradigms. Models trained on single-center, homogeneous data are prone to overfitting, which limits generalizability across institutions because of substantial heterogeneity in equipment models and scanning parameters. As reported in recent systematic and scoping reviews, a significant translational gap remains in the current literature. The vast majority of AI-related studies in spine surgery remain confined to evaluating model accuracy via internal validation, with limited external validation in multicenter, large-sample cohorts. Furthermore, a substantial proportion of these studies fail to adhere to standardized reporting guidelines for clinical AI interventions [such as the Consolidated Standards of Reporting Trials (CONSORT)-AI extension], hindering the transition from computational algorithms to reliable daily clinical practice[27].

Algorithmic "black-box" effect and clinician trust challenges

The deep learning models currently used in AIS surgical planning generally have inherent "black-box" attributes; their internal processes of complex nonlinear feature extraction and decision weight allocation are difficult to trace and interpret. Due to the lack of transparency and explainability, surgeons cannot ascertain the exact evidence-based rationale behind a model's recommendation for specific fusion levels or prediction of complications, which significantly reduces clinicians' willingness to adopt and trust these systems[28]. Furthermore, when recommendations generated by high-dimensional algorithms diverge from surgeons' empirical judgments based on traditional guidelines, how to balance the two and establish a safe and reliable human-machine collaborative decision-making mechanism remains an important clinical challenge.

Clinical workflow integration barriers and economic constraints

Currently, the vast majority of AI research targeting AIS remains limited to laboratory algorithm development or early clinical validation stages, and has not yet been fully integrated with real-world clinical workflows. The high initial deployment costs (such as computationally intensive intelligent navigation systems and 3D printing equipment) create substantial economic barriers, severely limiting the adoption of these technologies in primary care institutions. Robust cost-effectiveness analyses of AI-assisted AIS surgery are still scarce in the literature. The lack of long-term economic evidence makes it difficult for hospital administrators to justify these high initial investments, further hindering widespread clinical adoption. In addition, the standardized application of AI technologies requires spine surgeons to understand AI methods and develop appropriate operational skills, while targeted continuing medical education and systematic training systems are currently inadequate[29]. Furthermore, it is worth noting that poor user-interface and user-experience design (UI/UX) is an important but often overlooked obstacle to the real-world

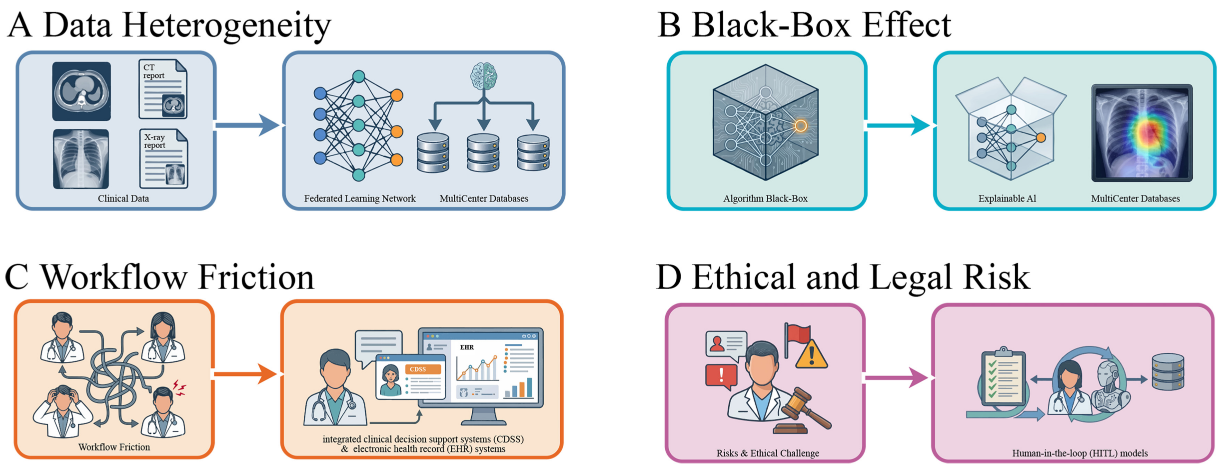

Figure 3. Barriers and solutions framework. A schematic mapping the four core translational challenges to their corresponding strategic solutions: (A) Data Heterogeneity, addressed by federated learning networks and multicenter databases; (B) Black-Box Effect, mitigated through explainable AI algorithms; (C) Workflow Friction, resolved via integrated CDSS and EHR systems; and (D) Ethical and Legal Risk, managed through HITL models. (Created with Adobe Illustrator by the authors.) AI: Artificial intelligence; CDSS: clinical decision support systems; EHR: electronic health record; HITL: human-in-the-loop.

implementation of high-precision AI models[30]. Although some algorithms demonstrate strong predictive performance in retrospective validations, their system designs often fail to meet the demands of time-sensitive operating-room workflows. Spine surgeons are already under a high cognitive load when performing complex 3D preoperative planning or real-time intraoperative navigation. If AI workflows are unnecessarily complex, parameter adjustments are not intuitive, or the systems require surgeons to switch their visual focus frequently between the real surgical field and external screens, they may cause operational fatigue and significantly reduce clinician adherence to these systems[30]. As highlighted by recent rapid reviews of the evidence in scoliosis care, the application of AI remains in a transitional phase. Despite demonstrating high internal accuracy in laboratory settings, the vast majority of current models have received limited external validation in multicenter, large-sample cohorts. Furthermore, weak clinical integration capabilities and the absence of standardized implementation protocols are major barriers to their translation into routine clinical decision-making tools[31].

Responsibility attribution and ethical/legal challenges in data privacy

As auxiliary decision-making tools, AI models may produce incorrect recommendations when facing extreme deformities or complex anatomical variations. If complications or long-term correction failures occur after model-recommended surgical plans are adopted, current medico-legal frameworks do not clearly define responsibility among algorithm developers, medical institutions, and chief surgeons[32]. Furthermore, the clinical and imaging data used for model training contain highly sensitive personal information; establishing a robust data-protection framework while enabling multicenter data sharing to improve algorithm performance remains an important ethical and legal challenge[33].

FUTURE DIRECTIONS

With continued growth in computing power and the availability of multimodal medical data, the role of AI in precise surgical planning for AIS is expanding from an auxiliary measurement tool to a decision-support system spanning the clinical pathway. To facilitate its effective clinical translation, progress is needed in the following four key dimensions [Figure 3]:

Overcoming data silos: building multicenter federated-learning networks and standardized databases

High-quality, multimodal, large-sample cohorts with longitudinal follow-up are essential for training robust AI models. In the future, greater multicenter collaboration is needed across countries and institutions to establish a unified data annotation paradigm (data ontology) covering imaging, clinical, and follow-up dimensions[34]. More importantly, federated learning and swarm learning architectures can support distributed training across heterogeneous multicenter datasets while keeping source data private, thereby addressing barriers to compliant data sharing and improving model generalizability.

Breaking the algorithmic black box: developing explainable AI and human-machine collaborative paradigms

To mitigate the inherent black-box nature of deep learning algorithms, future research should prioritize the development of explainable AI (XAI). By leveraging feature attribution techniques - such as Gradient-weighted Class Activation Mapping (Grad-CAM) - and advanced attention mechanisms, XAI can help explain the underlying pathological and anatomical basis of the models' diagnostic or prognostic outputs[35]. On this basis, a human-in-the-loop (HITL) framework could incorporate the implicit clinical experience of senior spine surgeons (such as tactile assessment of flexibility) into the models, combining computational capabilities with clinical expertise.

Overcoming translation barriers: facilitating seamless integration into real-world clinical workflows

Ultimately, the value of AI depends on its real-world clinical translation and accessibility. Future research and development should adopt a scenario-driven approach, focusing on the deployment of lightweight, highly robust Clinical Decision Support Systems (CDSS) that seamlessly integrate into the existing clinical workflows and decision-making practices of spine surgeons[36]. Integrated hardware and software should support these systems throughout preoperative assessment, intelligent preoperative planning, real-time intraoperative navigation, and dynamic postoperative follow-up. Concurrently, health economic evaluations should be incorporated prospectively to optimize deployment costs through iterative technological refinements. Ultimately, this will support the adoption of AI-based solutions in primary care and resource-limited settings, democratizing access to high-quality spine care[37].

Strengthening regulatory compliance: developing agile governance and ethical/legal frameworks

Rapid technological development must be supported by appropriate ethical and regulatory frameworks. In the future, it is necessary to establish and refine an agile regulatory review mechanism for medical AI devices, clarifying responsibility for adverse medical events caused by algorithmic bias in human-machine collaborative decision-making. Furthermore, standards for continuous, lifecycle-based algorithm auditing and compliant data use must be refined to balance patient privacy with scientific innovation[38].

CONCLUSION

AI is changing the clinical paradigm of surgical treatment for AIS, supporting a transition in precise surgical planning from "experience-based static morphological assessment" to "data-driven intelligent decision-making based on multimodal and biomechanical information". Through applications such as the automated extraction of high-dimensional preoperative deformity parameters, personalized selection of fusion levels and optimization of rod pre-bending, biomechanical adaptation of internal fixation systems, and prediction of long-term HRQOL trajectories, AI technology provides a potential methodological framework for the individualized surgical intervention for AIS.

Although the field remains constrained by practical challenges such as multicenter data heterogeneity, the inherent "black-box" attributes of deep learning algorithms, integration barriers into real-world clinical workflows, and unresolved questions of ethical accountability, the technological evolution of AI continues to show promise. In the future, with the widespread deployment of federated learning architectures in multicenter cohorts, advances in XAI, and especially the integration of AI with biomechanical approaches such as 3D spinal finite element analysis, intelligent decision-making systems could help bridge the current gap in clinical translation. Within human-machine collaborative decision-making frameworks, AI could support more data-driven and precise spine surgery, aiming to optimize individualized clinical benefits for AIS patients by balancing effective 3D deformity correction with long-term biomechanical homeostasis.

DECLARATIONS

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Authors' contributions

Made substantial contributions to the conception and design of the study and performed literature review and synthesis: Zhu K, Zhang Y, Liu J, Zhang Q, An Z, Mao Y
Performed literature search and selection and provided administrative, technical, and material support: Zhao R, Zhu J, Hang L

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool Gemini (version 1.5 Pro, released 2024-05-14) was used solely for language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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